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ARCING TRANSIENTS ON MULTI-CIRCUIT LINES

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Abstract

In several cases transmission line circuits with different nominal voltage levels run in parallel on same towers. Becomes faulty the lower voltage (HV or MV) circuit it initiates a Single or Three Phase Reclosing (SPR or TPR) during which the higher voltage (HV or EHV) circuits could cause a low current (secondary) arc in the ionized plasma cloud generated by former primary fault arc as a consequence of coupling with healthy phase conductors. Does not extinguish secondary arc till the faulty phase(s) reclosing SPR or TPR will be inefficient.

One goal of the paper is to study electromagnetic transients during dead time of the AR (Automatic-Reclosing) by simulation. Besides the author has invented and built a HV test circuit from lumped components to analyse above-mentioned phenomena.

Article shows main results having got by simulation and confirmed by actual HV tests as well as a plan of another HV circuit by means of which real network circumstances can be simulated correctly.

Inductive potential transformers and ZnO surge arresters are not disconnected from faulty phase during AR. Analyzing influences by these units on studied phenomena has been also carried out.

Keywords: EHV, HV, secondary arc, multi-circuit lines, EMTP, Automatic Reclosing, voltage escalation, test circuit, inductive potential transformer, ZnO.

1. Introduction

Importance of the multi-circuit lines increases in EHV long distance power transmission.

Double or multi-circuit lines can be used to magnify volume of the transmitted electrical energy or to increase reliability of the operation of transmission lines. Ownership of the land becomes more expensive in urbanised areas also in the countryside additionally so it is more difficult to find suitable land to build overhead lines in both areas. Running same or different nominal voltage overhead lines on same towers where it can be constructed is a cheaper solution than building up single towers for each circuit. This is advantageous concerning lines reliability and urban area site utilization but causes additional problems at the effective overvoltage-protection and the successful AR performance versus single towers cases.

Let me take some definitions: common length (running on the same towers) of the circuits with different nominal voltages calls s_c; length of the lower nominal voltage circuit running alone calls s_a (see *Fig. 1*).

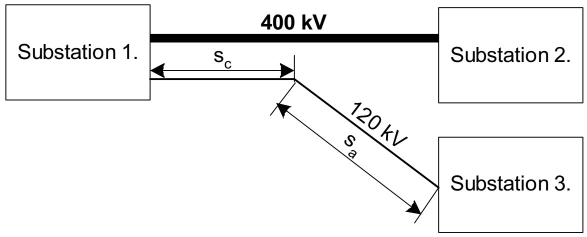


Fig. 1. The definition of s_c and s_a

1.1. Secondary Arc in a Single Circuit Line

Arises SPR on a single circuit transmission line circuit breakers disconnect the faulty phase at both ends of the line (see *Fig. 2a)*). After primary arc extinguishing a hot, ionised, plasma leader remains in its place.

A secondary arc can develop in this plasma cloud supplied by healthy phases being coupled with the faulty one. This low current (10÷150 A) secondary arc contains an induced component due to inductive coupling between phase conductors and a capacitive one caused by mutual capacitances (C_{AB}). The induced component may usually be neglected because of its low amplitude. The equivalent circuit of SPR [1] is shown by *Fig. 2b*).

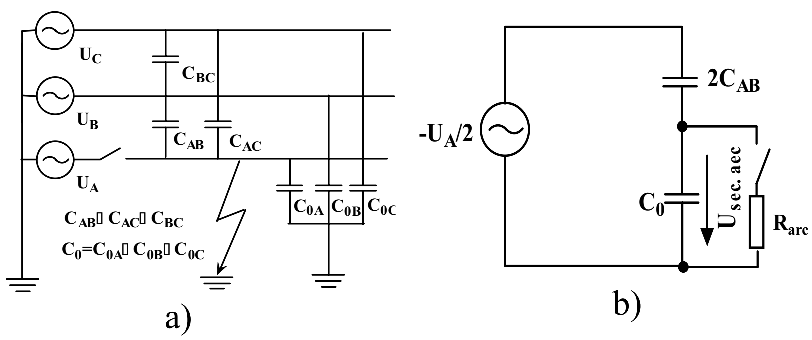


Fig. 2. Network configuration (a)) and equivalent circuit (b)) of the secondary arc at single circuit lines

Functions of the *Fig. 2b)* units are as follows: $-U_A/2$ and $2C_{AB}$ are Thevenin equivalent of the sound phases; C_0 represents the faulty phase earth capacitance; R_{arc} is resistance of the secondary arc; the switch simulates reignition and extinction of the secondary arc by switching on and off.

Dielectric strength of the remanent plasma channel has to be increased to a degree where switching-on-overvoltage that develops after the current-zero is not able to breakdown plasma channel resulting inefficient SPR. Does not arise the secondary arc final extinguishing till circuit-breaker reclosing SPR will be inefficient. Owing to consequences secondary arc is significant part of the SPR.

There are two types of the secondary arc:

Continuous: It generally exists immediately after primary arc, so arc channel contains ionized gas in great quantities. Arc extinguishing happens directly in neighbourhood of the 50 Hz current zero causing negligible current cut off. Reignition occurs at small potential with low current, so it seems to be a continuous arc ($I = 20 \div 150$ A_{peak}).

Intermittent: Arc channel is continuously getting cold including less and less quantity ionised gas. Therefore arc will be extinguished at greater voltage causing high current cut off and will be reignited at greater potential in every 50 Hz current zero breaking like as a well-known 50 Hz intermittent arc.

Secondary arc is influenced by several parameters. Some of them are deterministic (nominal voltage, length of the line, etc.); others are stochastic (wind velocity, fault location, primary arc current and duration, etc.). Effects of some parameters – mainly stochastic ones – are not cleared up exactly yet.

For evolving secondary arc length of its channel has to be equal at least to the length of the primary arc channel which according to the current of about 5÷10 kA is much more energized than the secondary arc owing to a significant smaller current. From these follows its pregnant thermal buoyancy on account of which arc is forcefully influenced by the environmental parameters, especially by wind velocity and wind direction ([2]). In calm secondary arc can burn up to 20÷30 seconds what is greatly longer than dead time of the SPR or TPR. On the other hand it can extinguish in 3÷5 periods (60÷100 ms) if wind velocity is high (> 5÷6 m/s). The shape of the arc channel is stochastic thus resistance, voltage, current of the arc are changeful producing fluent heat quantity. The reason of the final extinguish is that the voltage, which can sustain the arc, passes the potential-difference between the earth and the conductor disconnected, so arc is not able to be reignited in the next half period.

1.2. Multi-circuit Line Secondary Arc

Supply of the secondary arc is much more complex at this type of the lines than in the former case. If one of the conductors becomes faulty arising SPR cycle own healthy and the other circuit(s) phases supply secondary arc, each sound phase, through its mutual capacitance (see *Fig. 3a)*. To make an equivalent generator and equivalent mutual capacitance every mutual path of the supply has to be added. Thevenin equivalent of them are the U_{EQU} and C_{EQU} in *Fig. 3b*. If positions of the phases in any healthy circuit are spatial-symmetrical to the faulty phase their effects are negligible, because sum of these three phases is practically zero.

Other components of the equivalent circuit (*Fig. 3 b*) are interpreted in the same way as in the single-circuit (*Fig. 1b*) .

Secondary arcing process can work in multi-circuit lines during TPR since other lines can supply faulty phase(s). One of these possibilities can be seen with its equivalent circuit in *Fig. 3*.

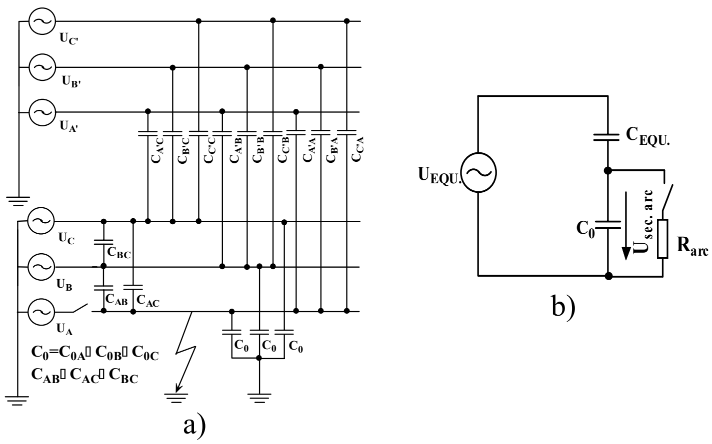


Fig. 3. Network configuration (a) and equivalent circuit (b) of the multi-circuit line secondary arc during TPR

Numerous combinations of the multi-circuit secondary arc can occur depending upon tower configurations of several structures and different fault possibilities.

2. Phenomena Studied

The author for creating simulation network with ATP-EMTP [4] (see *Fig. 4*) uses results of [3] dealing with possibilities of secondary arc in multi-circuit lines and simple calculations. This network can not mind accurate thermal conditions of the secondary arc plasma channel, but it gives correct results from the point of view of the studied phenomenon.

Different nominal voltage circuits can run parallel at greater or smaller distance on the multi-circuit line towers as mentioned in the introduction (greater or smaller s_c exists). If SPR or TPR occurs on the lower voltage circuit caused by a fault circuit breakers disconnect the faulty phase(s). After primary arc extinguishes the remanent ionised channel begins to separate into higher and lower conductivity sectors. The voltage on faulty phase(s) coupled from the higher nominal voltage circuit(s) and healthy phases of own circuit at SPR can reignite the remanent, ionised channel(s). If these reignitions are very short ($\sim 50\ldots 800\mu$s) with high amplitude current impulses transient current zeros of great value occurring at the end of each current impulse causes high restriking voltages. These voltages appear on disconnected, floating phase(s) and displace it (them) to high potential from the earth. This process is analysed particularly in this article included HV circuit tests.

An example of the analysed circuit combinations can be seen in *Fig. 4* [4]. On the 120 kV circuit a TPR has arisen whereby all phases of it will be disconnected from the supply system. Fault occurs at the end of the 120 kV line, 400 kV network is fed and loaded by an equivalent 400 kV generator through its supply system. Value of s_c for 400 and 120 kV circuits is 60 km; s_a equals to 0 km. R_{ARC} resistance of 100 Ω is based on registrations according to [5], represents the arc. Time-controlled switches connect the arc to the 120 kV line phase C whereby reignitions occur at set times. During this simulation arc extinguishes at the first transient current zero resulting fastest speed in growing of the floating (disconnected) phase conductor voltage.

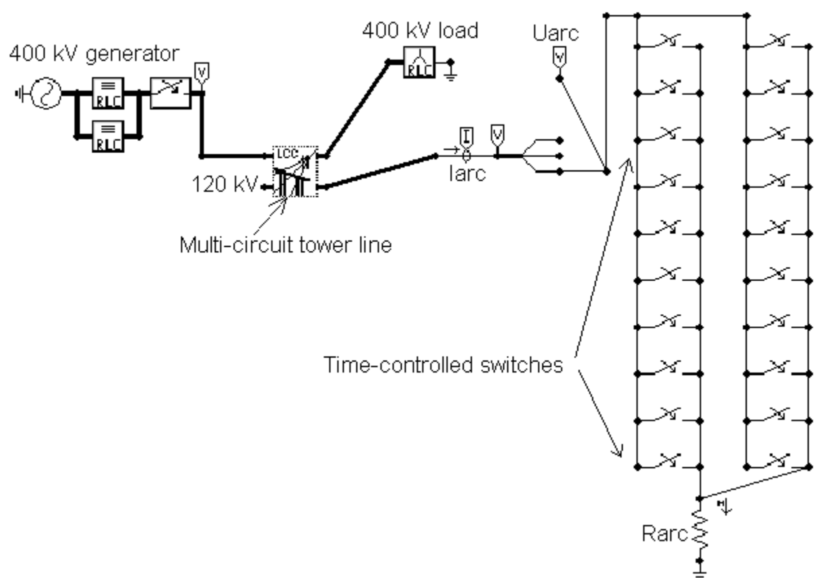


Fig. 4. One of the analysed circuit combinations [4]

Coupled voltages are different on each faulty phase namely distances between the faulty and the healthy conductors are distinct at the analysed multi-circuit tower. Coupled floating voltage amplitude ($U_{f\,\mathrm{peak}}$ = 30 kV) can be seen in *Fig. 5* at 5 ms point.

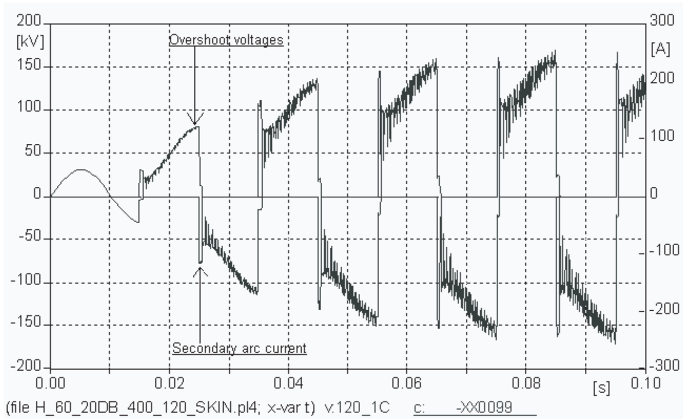


Fig. 5. The developed, floating voltage (left scale) and the secondary arc current (right scale) on the faulty phase at 400/120kV line

This voltage appears always on this phase conductor when the higher nominal voltage circuit is switched on. The accessible voltage maximum of this case ($U_{o,\max.}$ =~170 kV) can be obtained, exceeding the peak value of the nominal phase voltage on the 120 kV line (98 kV). Occurring the first reignition there is a possibility to get going floating voltage escalation and of great voltage developing causing an inefficient reclosing.

2.1. *Overshoot Process in Detail*

One part of *Fig. 5* is magnified in *Fig. 6*.

Reaching the highest value of the voltage in the actual half cycle (call overshoot voltage = U_o) arc is reignited caused by the time controlled switch to connect phase conductor to the earth (see 35 ms point in *Fig. 6*). Potential of the 120 kV phase disconnected drops to approximately –16.4 kV, value of the secondary arc current amounts to 160 A (see 0.4 ms width current impulse at 35 ms point in *Fig. 6*).

After twice travelling time of the transmission line (~400 μs) a slope transient current zero originates as a consequence of coming back an opposite sign current wave from the other end of the 120 kV line. The great di/dt generates a significant restriking voltage, superimposing on the previous value of the floating phase potential (–16.4 kV) displacing it to 69 kV. 50 Hz voltage coupled sits on this 69 kV voltage further growing potential till it reaches its highest value (U_{o+1}) in a half cycle. The transient oscillation on the 50 Hz voltage curve comes from the reflection of the voltage waves at the ends of the 120 kV line (similarly to the current

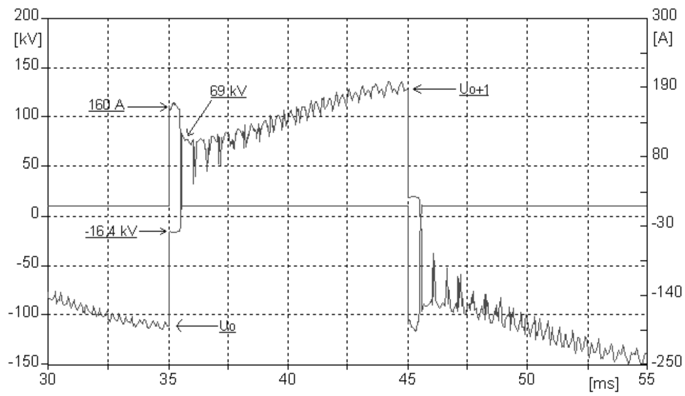


Fig. 6. A magnified part of *Fig. 5*

wave). Serial reactance of the conductor decreases its value continuously. The repetition of these restrikes causes an alternating potential growing of the disconnected phase (see *Fig. 5*) till arriving accessible voltage maximum ($U_{o\max.}$) depending on geometry of the tower and the arc resistance.

After that HV test is needed to verify the voltage escalation phenomenon.

3. Test Circuit

Because of limited device and financial possibilities a simple HV circuit has been built in the 400/220/120 kV GÖD substation of OVIT. Circuit diagram can be seen in *Fig. 7*.

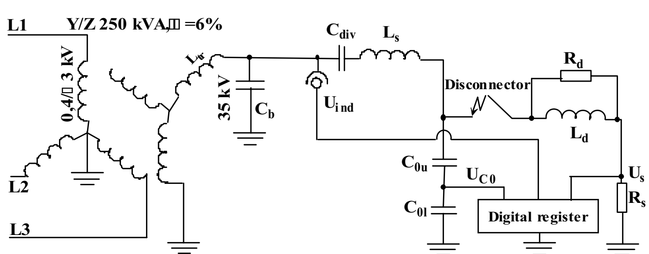


Fig. 7. The circuit diagram of the HV test

Test circuit is based on *Fig. 3b*. The Y/Z type 35/0.4 kV transformer represents the higher nominal voltage network; $L_{tr.}$ is the inductance calculated approximately from short-circuit impedance of this network; charge of the C_b amplifies the HV supply in such a way that the high peak current value can be evolved at the restrikes. The C_{div} simulates the capacitive coupling between the disconnected phase conductor and the sound phases; the L_s is the serial inductance of disconnected phase conductor. The capacitive divider (C_{0u} and C_{0l}) has two functions: First is to represent capacitance between the off-line phase conductor and the earth; sSecond is to measure the off-line conductor potential. Arc is carried out by an 120 kV, horizontal moving, manual actuated disconnector. The parallel R/L unit has two jobs too: on one hand to favour supply system by limiting value of the current impulse during restrikes and on the other hand to simulate transients of the 120 kV circuit. *Table 1* shows values of the circuit units, which are real elements of the Hungarian UHV transmission network (i.e.: high-frequency blocking circuit, coupling capacitor).

Table 1. The units with magnitude of the circuit

$C_{\mathrm{div}}(\mu\mathrm{F})$	0.093
$C_{Ou}(\mu\mathrm{F})$	0.002
$C_b(\mu\mathrm{F})$	0.2
$R_s(\Omega)$	0.1
$R_d(\Omega)$	200
L_d (mH)	1
L_s (mH)	0.15

One part of the HV test circuit can be seen on *Fig. 8*, from left to right are the L_d, 2 pieces R_d (2*100 Ω) and the capacitive divider.

In case of 400 kV higher nominal voltage and occurring SPR on the lower nominal voltage system (120 kV) the floating potential process of the phase disconnected can be seen on *Fig. 9* using LCC model of [4]. The LCC model (Line Cable Component) maps the transmission line with frequency depending response characteristics and damping. Both are calculated from the tower shape or from the cross-sectional layout of the cable using other electrical parameters.

Fig. 10 shows simulated primary voltage U_{C0} based on HV test circuit of *Fig. 7.* with values in *Table 1.*

Fig. 8. One part of the HV test circuit

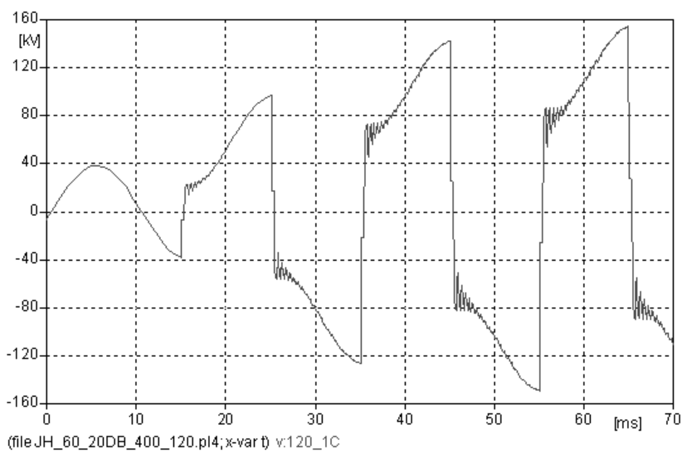


Fig. 9. The voltage escalation on one 120 kV phase of the 400/120 kV transmission line using LCC model of [4]

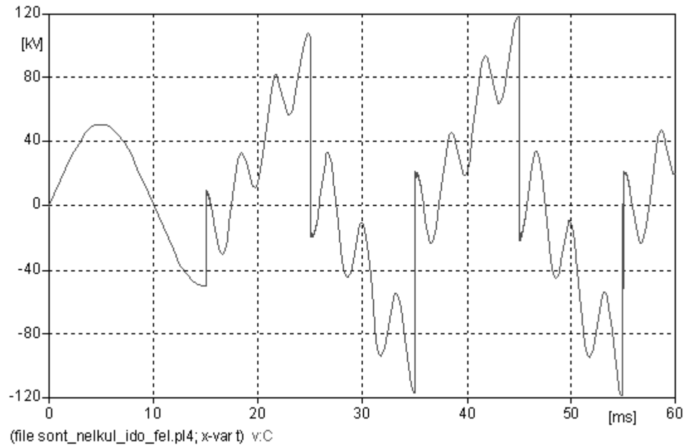


Fig. 10. The outcome of the simulation with values of *Table 1*

Fig. 9 and *Fig. 10* voltage curves are similar except 300 Hz voltage oscillation, which is superimposed on the 50 Hz voltage escalation after arc extinguishing. Explanation is as follows: test circuit contains lumped units on contrary to the LCC model of [4] which uses frequency depending response characteristics and damping, beyond that it is build up as distributed parameter network. Coming from above $L_{\mathrm{tr.}}$ and C_b compose a serial oscillation circuit of which oscillation frequency amounts to 300 Hz.

Voltage unit on *Figs. 9* and *10* is in kV, but the HV test circuit floating point voltage unit (U_{C0}) on *Fig. 11* is V as a consequence of the capacitive divider ratio (1000:1).

The 300 Hz phenomenon is visible on the oscillogram too, but with lower amplitude caused by non-mapped damping (i.e. greater R/X ratio of the test circuit versus in simulation) than in the simulation.

After *potential shifting* (see label on *Fig. 11*) in every reignition period through about 3 ms voltage does not change because of the following reasons.

During this time an indirect power arc evolving process passes off [1, 8] that means impulse arc (like the studied phenomenon) can transform into power one (continuous, 50 Hz) through fast, multiple reignitions. Power arc can not develop at the end of the process on account of low powered supply. From this process on oscillogram of *Fig. 11* only an almost unvaried potential can be seen first of all because of sampling rate of registration equipment being not high enough for very fast changes. Meanwhile multiple reignitions with current impulses did not allow to evolve the 50+300 Hz voltage in this ‘problematic’ 3 ms. This ‘multiplied process’ is influenced hardly by the circuit and environmental parameters (i.e. calm, wind

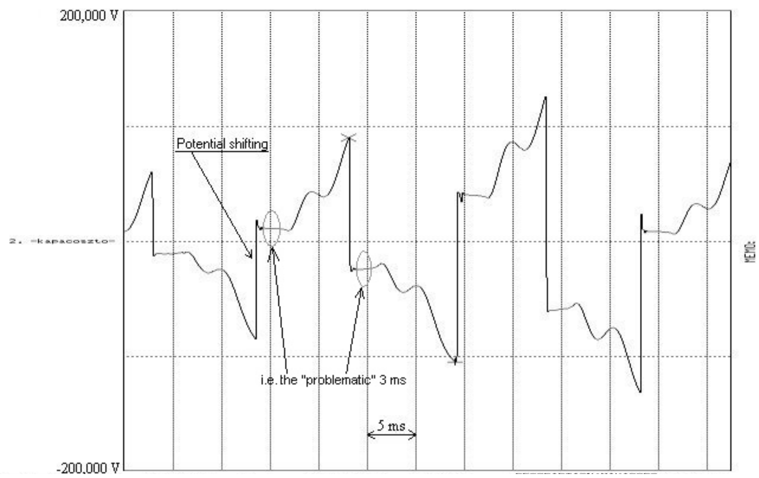


Fig. 11. The voltage of the capacitive divider (UC0) in the HV test circuit

velocity, geometrical building-up of electrodes, etc). Under test condition showing on oscillogram advantageous circumstances have supported multiple reignitions.

Besides the '3 ms interval' – also under limited practical registration conditions – a voltage escalation can be seen several times (see *Fig. 11*) in test records matching both simulations on *Figs. 9* and *10* in frequencies, voltage amplitude and shape. It can be determined: voltage escalations introduced in chapter 2.1 have evolved repeatedly during the HV test.

The continuous arc current has to be limited to $0.8 \div 1\ A_{\text{eff}}$ by C_{div} and parallel R_d/L_d units for the low-powered supply. Heat capacity of this current is not enough to evolve 50 Hz continuous arc at same length as in case of intermittent one; nevertheless continuous arc can materialize several times during HV test but with only smaller length. This can be seen on a detail of the voltage record and on frame of the arc video in *Fig. 12*.

The curve of *Fig. 12* shows clearly that the 50 Hz power arc interrupts near to current zero and reignits at low voltage at each half period.

Continuous arc can take shape at the same length as in the case of the intermittent one by using high power supply HV test circuit.

4. Test Circuit for Correctly Simulating Real Network

We have got lots of information about studied phenomena by making HV test. To make detailed and correct analysis in a not too complicated HV test circuit it is necessary to meet test critera as follows:

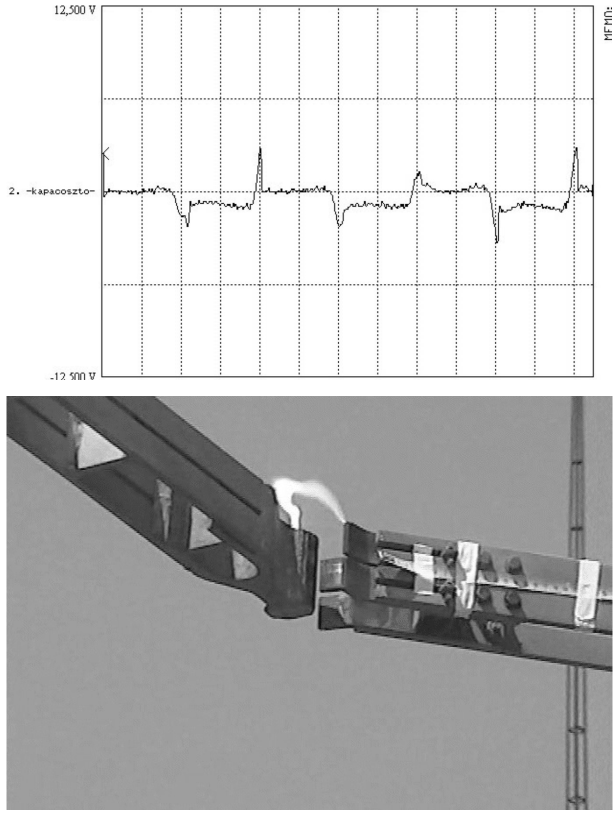


Fig. 12. The 50 Hz arc voltage on the record and the video

Disconnected phase is constructed from Π units, building from capacitances and inductances. Wave impedance of the Π units has to be equal to one of the disconnected phases.

- The higher nominal voltage system is fed by a power supply whose parameters are similar to the real network. (Short-circuit capacity has to agree with real one, but it has to amount at least to one hundred MVA.)
- The main influence parameters (i.e.: wind velocity and direction) of the secondary arc can be controlled.
- Required accuracy in the registration has to be ensured (i.e. by means of near non-inductance R_s in current measuring with registration equipment of sampling rate high enough).

HV test circuit (i.e. analysed 400/120 kV 60 km length) fitting to these criteria can be seen on *Fig. 13*.

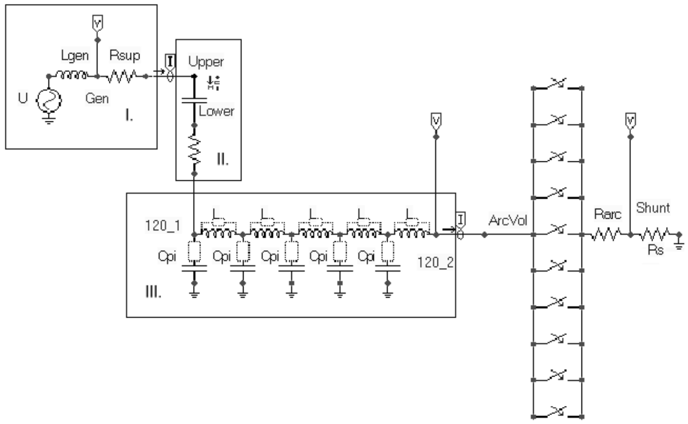


Fig. 13. HV test circuit for simulating real network conditions

Architecture of the circuit is similar to *Fig. 7*, it has four main parts:

I.: *Higher nominal voltage supply*: Its duty is to provide stable supply voltage and required power build from a 400 kV generator or transformer and the feeder transmission line inductance.

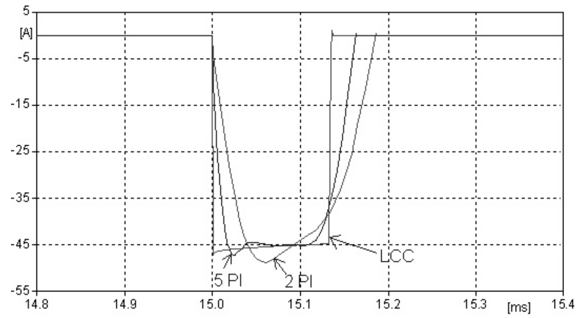
II.: *Connection between circuits*: Capacitor's adequate value is determined by length of transmission line studied for connecting supply to the disconnected phase. The connection point to the Π units is not determinative from studied phenomenon aspect. Resistor is the resistance of the capacitor and the feeding.

III.: *Disconnected phase*: It builds from Π units mentioned before. Length of the transmission line determines values or numbers of the capacitances and inductances.

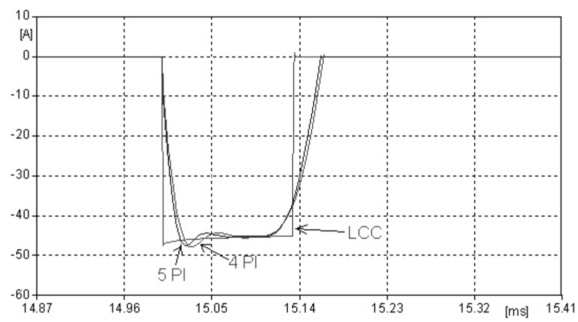
On the right side of *Fig. 13* non-marked part contains switches that simulate reignitions, secondary arc (R_{arc}) and arc current measuring shunt (R_s). In a test circuit this part can be executed by means of electromechanical devices (i.e by pendulum form electrode structure) being able to change arc length ignited at switching on voltage. Besides pendulum instanced there are more possibilities for carrying out these devices, having adequacy enough to map this part of the test circuit.

Transmission line can be precisely simulated by infinite number, lossy Π units but impossible to build them on account of financial and physical causes. Author determines minimal number of the Π units of the studied double-circuit transmission line 120 kV phase conductor disconnected (see *Fig. 13*) from the point of view of the studied phenomena with acceptable exactness.

It can be taken in two steps: first means comparing of current restriking impulses (form, amplitude) of simulated real network (= the LCC model of [4]) and of circuits out of Π units with different number. Results are shown on *Fig. 14a)* and *b*).



a.)



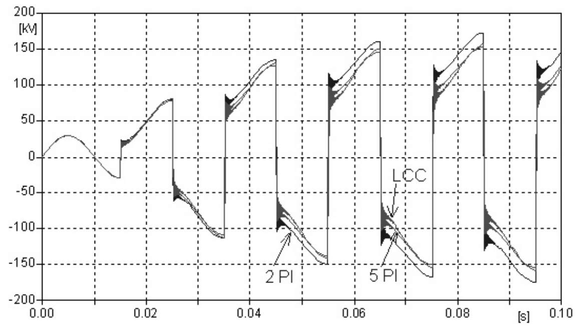
b.)

Fig. 14. 2, 4, 5 Π units and the LCC model [4] are compared by the current restriking impulses

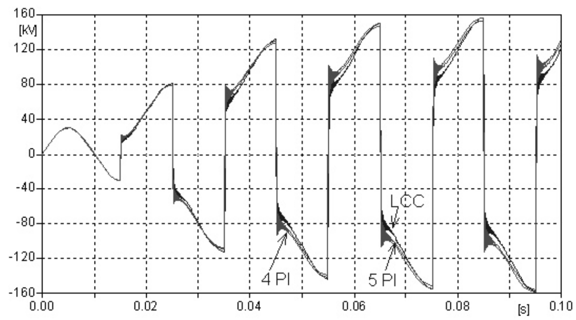
Fig. 14a reflects curve belonging to 2 Π units is not really exact as cause shape to be rounded at beginning and ending of current impulses. From the *Fig. 14 b)* entering edge with 5 Π units can be seen better than with 4 Π ones but current back-tails are identical. Negative-going edges have influence on potential shifting after arc extinction so in this regard circuits out of 4 and 5 Π units are about equivalent. Only 15÷20 or more Π units result significant greater rate of decrease $|\mathrm{d}i/\mathrm{d}t|$ at current back-tail.

Second step: Influence of the number of Π units on the potential of the floating point. Answers to this question can be read from *Fig. 15 a* and *b*.

Network out of 2 Π units produces significant greater potential ($\sim$16 kV $\approx$ 10 %) than 5 Π units and LCC ones (see *Fig. 15. a*). Potential differences in networks out of 4 and 5 Π are smaller by 3 % compared to LCC one, so they are matched.



a.)



b.)

Fig. 15. 2, 4, 5 Π units and the LCC model [4] are compared by the floating voltage shape

From comparison above can be declared; network out of 2 Π is not exact enough from the point of view of current impulse and voltage escalation. But 4 and 5 Π units concerning current impulses and voltage escalation exactness match together and they are correct enough from the point of view of the studied phenomenon. Financial possibilities and components being acquirable determine first of all the number of Π units. Greater number of Π units, of course, causes smaller inaccuracy in mapping.

5. Influence of the Trasnmission Line Passive Elements

When faulty phase is disconnected by circuit breakers at the ends of the transmission line inductive potential transformers (capacitive one has no effect on the phenomenon) and ZnO surge arresters are left connected on faulty phase. These devices affect phenomena studied during dead time of AR rate depending upon characteristics of the ZnO and the inductive potential transformer.

5.1. Inductive Potential Transformer

The inductive potential transformer is a galvanic connection between the earth and the phase conductors. Based on characteristic of a 120 kV device [6] the nominal current amounts to about 0,2 A effective. When these potential transformers take on both ends of the 120 kV part of the transmission line their current can be increased pro rata on escalation voltages up to ~7 A. The $U_{o,max}$ decreases in a non-essential rate (~13 %) as a consequence of the conductor charge decrement due to increased discharge by inductive potential transformer. The effect can be seen on *Fig.* **??** (see label Potential transformer).

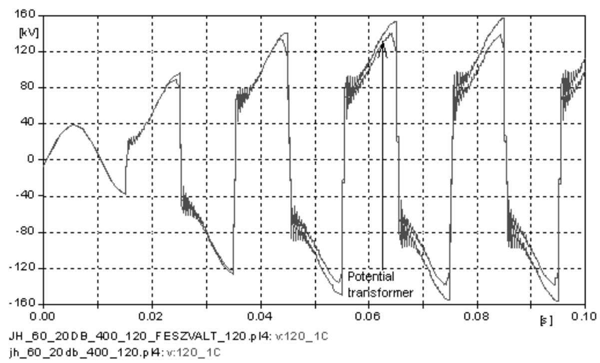


Fig. 16. The decreased potential caused by the inductive inductive potential transformer

This passive element cannot interrupt voltage escalation and its decrease effect on probability of unsuccessful reclosing is negligible.

5.2. ZnO Surge Arresters

Function of this circuit element is to protect devices on phase conductor from non-allowable overvoltages. Derogation rate depends upon nominal voltage of the line, rules of the standards and characteristic of the surge arrester. Reaches potential of the disconnected phase caused by voltage escalation break point of the arrester it takes off charge of the conductor. Its' rate depends upon characteristic of the arrester and of the conductor charge.

Taking a typical surge arrester [7] to either end of 120 kV line being part of a 420/120 kV double-circuit system voltage escalation cannot change as $U_{o,max}$ does not reach break point (160÷170 kV) of the arrester. If, however, floating voltage is higher (about 55 kV) $U_{o,max}$ will also be higher as it is shown on simulated 750/120 kV line of *Fig. 17* and arrester operates (see curve 'MOV'). Tower shape of this line is similar to 400/120 kV lines except insulation distances to earth and to higher nominal voltage phase conductors.

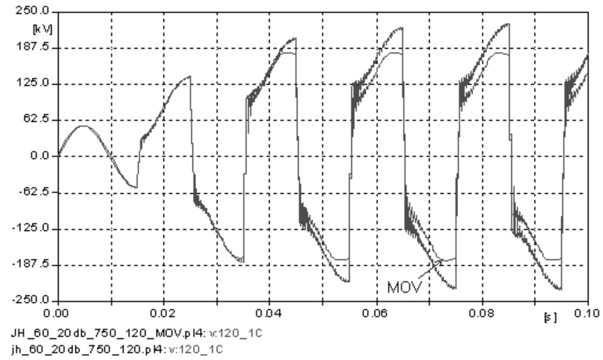


Fig. 17. The influence of the ZnO surge arrester on the voltage escalation at the 750/120 kV transmission line

Difference between maximal values of the time functions is more significant than in case of inductive potential transformer ($\sim$50 kV $\approx$ 20 %). Even so ZnO surge arrester cannot inhibit development of the phenomena studied and cannot make pregnant dropping in probability of unsuccessful reclosing similar to the action of the inductive potential transformer.

6. Conclusions

1. Contains secondary arc of the lower nominal voltage of the multi-circuit line very short ($\sim$50...800 μs) and high current impulses each transient current zero causes great restriking voltages as a reason of the voltage escalation in the faulty phase(s). Repetitive current impulses can ionise the remanent gas cloud(s) continuously till the reclosing; consequently AR will be probably inefficient.
2. A HV test circuit is made in which voltage escalation phenomenon is verified.
3. Using results of the test carried out another HV test circuit is designed being capable to simulate real network correctly.
4. Basing on simulations by the author it can be established: 4–5 Π circuit-units are enough to map studied phenomena of the 120 kV phase conductor disconnected from the transmission line by an AR with permissible inaccuracy.
5. Two passive elements (inductive potential transformer and ZnO surge arrester) having been not disconnected from the transmission line during AR cannot disqualify voltage escalation but they can decrease its maximal value.

Acknowledgement

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